New RPCs for the phase-2 CMS/LHC experiment and an application to particle therapy

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On Behalf of the CMS Collaborations
CMS in LHC
RPC detector system for fast particle selections

- Fastest response radiation detectors
- In LHC, we use them for fast muon selection
- Gaseous detectors in a limited proportional mode (avalanche mode)
- Phenolic based double-gap model
  - 2 mm gaps for the current system
  - 1.4 mm gaps for improved RPCs

Discovery of Higgs:

A. Salam, Elementary Particle Theory, p369, 1969
S. L. Glashow, J. Iliopoulos, and L. Maiani,
In the muon detector section

DTs and CSCs for tracking

RPCs for triggers
**Current RPCs System in the CMS**

**Barrel RPCs**
- 6 stations (layers)
- Fully covering up to $\eta = 0.8$
- Partially covering up to $\eta \sim 1.2$

**Endcap RPCs**
- 2 wings (RE+, RE-)
- 4 stations in each wing
- Covering $0.92 < \eta < 2.4(5)$

\[
\eta = \frac{1}{2} \ln \left( \frac{|p| + p_L}{|p| - p_L} \right)
\]

\[\vec{v} \rightarrow c \quad \eta = -\ln \left[ \tan\left( \frac{\theta}{2} \right) \right]\]

$\eta = 0$

$\theta = 90^\circ$

$\theta = 0^\circ$

$\theta = 10^\circ \rightarrow \eta = 2.44$

$\theta = 45^\circ \rightarrow \eta = 0.88$

Monday, November 13, 2017

2017 ICABU, Gyungju, 16th November
RPC System Upgrade

In Phase-2 (2025-), the LHC luminosity up to maximum $5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

1. **CONSOLIDATION** of the present system
   The current RPCs cover $0 < |\eta| < 1.8$ with 1056 RPCs. Should maintain the excellent performance of the detector system in the HL-LHC conditions (rates and longevity).

2. **EXTENSION** at high eta ($1.8 > |\eta| < 2.4$)
   We improve the CMS RPC system with new 72 RPCs with improved technology.
   - Better position & time resolutions
   - Capable of 2 dimensional measurement
   - Higher rate capability (> 2 k cm$^{-2}$)

3. **ECOGAS**
   R&Ds for RPC operation gases with a lower GWP (Global Warming Potential)
The RPC system has been certified for 10 years of LHC (at nominal luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$) at maximum rate of 300 Hz/cm$^2$ and 50 mC cm$^2$. The CMS RPC system has to be certified for the future HL-LHC running (luminosity of 5 $\times 10^{34}$ cm$^{-2}$ s$^{-1}$).

A dedicated irradiation test at GIF++ is ongoing since 2016 with four RPC chambers:

- One RE4 and one RE2 always at HV on: “irradiated”
- One RE4 and one RE2 always off: “reference”

1. Monitoring detector currents and noise rates
2. Detector performance (efficiency, cluster size, etc) measured 3-4 times/year with muon beam with and without presence of gamma background.
Extension of the CMS RPC system with improved RPCs

RE3/1 in ME3/1

RE4/1 in ME4/1

650 mm
Collar

19 mm
Collar

146 mm

80 mm

Neutron shielding

Beam line

Y

Z

High el. board

Low el. board

Neutron shielding

85 mm

4 mm

10 mm

Neutron shielding

ME3/1

ME3/2

YE4

YE3
Extension of the RPC trigger system up to \( \eta = 2.5 \).

In the Phase-2 LHC, the maximum background rate \( \sim 700 \text{ Hz cm}^{-2} \).
\( \rightarrow \) Requires a rate capability \( > 2 \text{ kHz cm}^{-2} \) (a factor 3 higher)

**How to enhance the iRPC performance?**

1. **Reduce electrode resistivity** \( (1\sim6 \times 10^{10} \Omega \cdot \text{cm} \rightarrow 0.9\sim3 \times 10^{10} \Omega \cdot \text{cm}) \)

2. **Adopt detector properties of fast timing RPCs for trigger RPCs**
\( \rightarrow \) Better time \( (\leq 1 \text{ ns}) \) and position resolutions
   Reduction of the avalanche charge by combining thinner gas gaps with more sensitive amplifiers in FEBs, higher S/N ratio and larger dynamic range.
\( \rightarrow \) Improving the detector sensitivity by a factor 3 or larger

3. **2-dimensional trigger measurements**
   3 mm in azimuthal and 2 cm in radial directions
\( \rightarrow \) **Now, we call the new CMS iRPCs are coarse trackers**

4. **Reduce the working point (WP) high voltage (HV)**
   9.4 (9.6) kV \( \rightarrow \) \( \sim 7.2 \text{ kV} \)

<table>
<thead>
<tr>
<th></th>
<th>RPC</th>
<th>iRPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap &amp; Electrode</td>
<td>2 mm</td>
<td>1.4 mm</td>
</tr>
<tr>
<td>Resistivity ( (\Omega \cdot \text{cm}) )</td>
<td>(1-6 \times 10^{10} )</td>
<td>(0.9-3 \times 10^{10} )</td>
</tr>
<tr>
<td>Strip pitch</td>
<td>2-4 cm</td>
<td>0.7-1.2 cm</td>
</tr>
<tr>
<td>FEBs threshold</td>
<td>150 fC</td>
<td>&lt; 50 fC</td>
</tr>
</tbody>
</table>
Front-end electronics: **PETIROC ASIC + TDC**

- 32 channels
- low noise
- gain 25
- fast pre-amplifier and fast discriminator in SiGe technology → time resolution (jitter) <100 ps
- Readout double coordinate: $\phi$-$r$ position (2D)

Cosmic-ray test using 10cm x 10cm plastic scintillators

$R = L/2 - v \times (t_L - t_R)/2$

$\sigma(R) = v \times \sigma(\Delta t)/2$

$\sim 1.8$ cm

$\phi$ resolution $\sim 3$ mm

96 strips (0.2083°)

**Work in progress**

40 cm x 70 cm Rectangular RPC
Large-size RPC tested with 100-GeV muons and gammas at GIF++/CERN

13.9 TBq $^{137}\text{Cs}$
R&Ds of new ecogas mixtures

Has found new gas mixtures with much lower GWP!
50% Tetrafluoropropene HFO-1234ze (C$_3$H$_2$F$_4$): GWP = 6
45.2% CO$_2$: GWP = 1
0.3% SF$_6$: GWP = 23900
4.5% C$_4$H$_{10}$: GWP = 3.3

HFO: $\alpha$ less then C$_2$H$_2$F$_4$, working voltage increasing

CO$_2$: quencher to reduce the working voltage.

Test with iRPC 1.4 mm:
✓ High efficiency
✓ WP HV increasing of $\sim$ 1.5 kV, but less than the current CMS RPCs (10 kV)

GWP$_{tot}$ = 73
Timing RPC technology to trigger RPCs

Tsinghua low resistive glass (ρ ~ $10^{10} \Omega \cdot \text{cm}$)

- Mosaic technology → panel shape multi-gap RPCs
- Time resolution ~ 60 ps
- Position resolution ~ 1.5 mm

Gas gap number: 5
Gas gap width: 250 μm
Glass thickness: 0.7 mm
Glass bulk resistivity: ~ $10^{10} \ Ω \cdot \text{cm}$
Mosaic interface: glass directly mosaic together

Strip number: 44
Strip shape: trapezoidal (6 mm/8 mm)
Strip interval: 3 mm
Strip length: 1 m
Conclusions and Milestones (CMS RPC system)

Preparations for the Phase-2 LHC experiment (2025-)

1. For the consolidation of the existing CMS RPC system, the longevity study using prototypes are ongoing at GIF++/CERN.
   ✓ The current RPC system has to be certified for the future HL-LHC running (Phase-2 LHC with a maximum luminosity of $5 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$)

2. Completion of the RPC coverage of up to $\eta = 2.5$
   ✓ The baseline detector design for the thin-gap iRPC is now well defined.
   ✓ A large prototype RPC has been successfully tested up to 4 kHz cm$^{-2}$ at GIF++.
   ✓ The detector sensitivity has been enhanced by a factor 3 with Th = 50 fC.
   ✓ WP HV at $\sim 7$ kV ($\sim 9.5$ kV for the current RPCs)
   ✓ But, a few different model including glass timing RPCs are still considered.

3. Eco Gas Study
   ✓ Promising eco-gas mixtures are just identified.
   ✓ Systematic tests with TDC and FADC are on going.
   ✓ Longevity test of iRPC with new eco gas mixture @ GIF++ is essential.
MRPC technology for Range Verification in Particle Therapy
Motivation of R&Ds

On-line verification of delivered doses in proton and carbon ion radiotherapies for quality assurance of hadron therapy treatments.

→ Range verification by measuring prompt gammas
  - In-beam PET (positron emission tomography)
  - SPECT (single-photon emission tomography)
  - Compton camera

Fixed carbon beam line at HIMAC

Proton-beam Gantry at Samsung
**In-beam PET**

Coincident measurement of 511-keV gammas emitted from only β decays of $^{11}$C, $^{13}$N, $^{15}$O

- Excellent resolution < 2 mm (Converged vertex images)
- Small field sizes
- Expensive

**Collimation for single $\gamma$**

Measurement of prompt gammas emitted from all excitation lines (> 0.5 MeV)

- Resolution < 5 mm
- Very low tagging efficiency for 2D imaging
- Large field sizes
- Cheep

**Compton camera**

Tracking all gamma rays

- Best efficiencies
- Difficult tomographic process
- Poor position resolution (diverged vertex)
- Expensive
Simulations for beam-induced secondary particles

Using a GEANT4 program (2008 version), simulations for

- Prompt and delayed gammas of the excitation lines of nuclei and Bremsstrahlung occurred in biological tissue
- Gammas, neutrons emitted from biological tissue
- Vertex positions, emission angles, energies

![Graphs of gammas and neutrons for 44 MeV and 190 MeV protons]

44 MeV protons (0.5 M)

190 MeV protons (0.5 M)
Estimation of Detector sensitivity (GEANT3) for a 8 glass-stacked MRPC (six-gap MRPCs)

Maximum Q. E. via Compton scattering = 0.041 at $E_\gamma \sim 3$ MeV for $d = 0.5$ mm

Maximum Q. E. via Compton scattering = 0.058 at $E_\gamma \sim 4$ MeV for $d = 1.0$ mm

→ Realistic detector sensitivity for all energies of gammas (x-y matched) ~ 0.02
Expected particle rates on the collimator (for ten minutes after beam off)

<table>
<thead>
<tr>
<th>Beam energy of proton</th>
<th>γ signal rate on collimators</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 MeV</td>
<td>~ 2 kHz cm⁻²</td>
</tr>
<tr>
<td>100 MeV</td>
<td>~ 12 kHz cm⁻²</td>
</tr>
<tr>
<td>190 MeV</td>
<td>~ 25 kHz cm⁻²</td>
</tr>
</tbody>
</table>

Expected detection rate (beam off condition)

Mean Q.E. for gammas at 8-stacked glass MRPC (6 gaps) ~ 0.02
Collimator efficiency ~ 0.02 (single) / 0.005 (double)

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<th>Beam energy of proton</th>
<th>γ detection rate on the detector</th>
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<tr>
<td>44 MeV</td>
<td>~ 0.8 Hz cm⁻² / ~ 0.2 Hz cm⁻²</td>
</tr>
<tr>
<td>100 MeV</td>
<td>~ 5 Hz cm⁻² / ~ 1.2 Hz cm⁻²</td>
</tr>
<tr>
<td>190 MeV</td>
<td>~ 10 Hz cm⁻² / ~ 2.5 Hz cm⁻²</td>
</tr>
</tbody>
</table>

For 44 MeV proton beam,
the actual rate (400 s after beam off)
  = 4.7 Hz cm⁻² (single collimator)
  ~ 0.7 Hz cm⁻² (double collimator)
→ Larger than the expected rate by GEANT4
✓ Collimator efficiency might be underestimated.
✓ Neutron driven gamma backgrounds in the detector.
GEANT4 simulation for 190 MeV protons
FWHM = 3 cm
Phantom size (biological tissue) = 30 cm x 16 cm x 16 cm

Dose distribution along the depth

Dose distribution in the horizontal plane

Vertex distribution of γ on the horizontal plane

Vertex distribution of γ on the horizontal plane

Counts/bin

Depth (1 bin = 1 mm)

Depth (1 bin = 2 mm)

Depth (1 bin = 2 mm)
Basic R&Ds of MRPCs for

- Position sensitive measurements for gammas applied to
  - PET and in-beam PET (511 keV)
  - In-beam SPECT using MRPCs (> 0.5 MeV)
- Expected rate capability (manufactured with ordinary glass) \( \approx 100 \text{ Hz cm}^{-2} \)

A prototype 6-gap MRPC

- Thickness of a single gap = 0.36mm
- Thickness/dia. of spacers = 0.35mm/4mm
- Spacers guarantee better uniform sensitivity for gammas than fishing rod
- Active area = 16 x 16 cm\(^2\)
- Thicknesses of glass
  - Outer electrode = 1.10 mm
  - Inner electrode = 0.45 mm
Readout strips

- 1-d strips for 1d imaging with 5-mm pitches
  Then, have to assign a separated detector to each direction

- 2-d strips for 2d imaging
  - Orthogonal x pads and y strips
  - Short strips → neglecting impedance matching
  - Pitch = 5 mm (strip width = 2.0 mm)
  - Position resolution ~ 2 mm
Gas: 90% TFE + 10% iC₄H₁₀

Typical HV: 9.0 kV ~ 9.5 kV

Typical strip multiplicity: 2 ~ 5

32-ch front-end electronics manufactured with commercial preamp chips (voltage sensitive)

- Input impedance = 20 Ω
- Gain = 200 mV/mV
- Ethernet communication for FEBs
- LVDS output pulse width = 70 ns (fixed)
- Minimum sensitivity ~ 0.1 mV (~ 20 fC)
- Time resolution ~ 100 ps

Threshold = 1.5 mV

64-ch multi-hit TDC

250 Hz clock triggers with a 64-μs gate width

Gas: 90% TFE + 10% iC₄H₁₀

Typical HV: 9.0 kV ~ 9.5 kV

Typical strip multiplicity: 2 ~ 5
64 x 64 pixels images
# of gamma hits per pixel ~ 170
Resolution ~ 2 mm

Spanner: stainless, 0.6 mm ~ 1.2 cm
Scissors: stainless, ~ 0.8 mm
Coins: brass, 1.0 ~ 2.0 mm

Half attenuation length of stainless for 661.7 keV gamma ~ 6 cm
**Beam test at KIRAMS**

- Use 20-mm thick PMMA as a phantom
- Proton beam
  - Energy = 44 MeV
  - FWHM ~ 30 mm at 70 cm from the vacuum beam exit
- Beam current = 1 nA & 10 nA
- Collimator
  - 5-cm thick lead bricks
  - 4 mm holes with a 10x10 mm² pitch
Beam-off condition

Gamma decays with finite half life times and positron annihilated 511-KeV gammas
($^{11}\text{C}$, $^{13}\text{N}$, and $^{15}\text{O}$)

Measured gammas for 400 s after an irradiation of 10 nA 44-MeV protons
(FWHM ~ 3.0 cm) on 20-mm thick PMMA for 400 s.

✓ TDC window = 65 μs
✓ Triger rate = 250 Hz
→ Actual time to tagging gamma=6.5s
✓ HV = 9.1 kV

Using a 10-na beam with a single collimator layer, measured gamma hits
= 7,850

**beam halo** image of secondary gammas induced by neutrons passing
through the collimator holes and by activating the detector materials.
Using two layers of collimators (beam-off condition)

Measured gammas for 400 s after an irradiation of 44-MeV protons on 20-mm thick PMMA.

- TDC window = 65 μs
- Trigger rate = 250 Hz
- Actual time to tagging gamma = 6.5 ns
- HV = 9300 V
- Effective gamma hits = 1,200
Conclusions and Milestones (Particle Therapy)

Conclusions: have examined and proven the basic technology using a MRPC for proton beam range verifications

- Simulations for prompt gammas to utilize all spectral lines of the beam driven excitations
- Confirmed the detector sensitivities and the resolution for the 2d images
  - Image resolution for 662 keV gammas = 2 ~ 3 mm → good enough for beam imaging
- Obtained images of induced gammas by 44 MeV proton beams of KIRAMS
  
  Gamma images obtained for proton beams for 400 s right after turning off the proton beam (actual gamma tagging time = 6.5 s).

Milestones

- Beam test using cyclotrons at Proton therapy facilities
- Design of the trigger/data-transfer electronics
  - Maximum rate ~ 10 kHz
  - Gamma-tagging dead time < 50%
  - LVDS-signal latching in a FPGA
  - Ethernet (USB3) data transfer to DAQ PC

For a typical therapeutic beam energy (~ 200 MeV)

Time to measure for 100 s after beam off → high statistics of ~ 200 kγ
BACKUPS
Charge distribution near WP (Fresh ADC)
Streamer-free operation with 1.4-mm double gap RPC

WP at $T_h = 400 \mu V (60 \text{ fC})$ at $HV = 6.91 \text{ kV}$

- ID: 1001
- Entries: 511
- Mean: 1.562
- RMS: 1.713

$HV = 7.37 \text{ kV}$

- ID: 1002
- Entries: 511
- Mean: 5.551
- RMS: 3.842
Technical validation for 1.4-mm double-gap model
Detector performance to high-rate background

(Cosmic rays and 5.55 GBq gamma source at KODEL)

**The shift of HV$_{50}$ due to a rate** of ~ 2 kHz cm$^{-2}$
~ 130 V $<<$ efficiency plateau size (> 400 V)

**WP efficiency drop** at ~ 2 kHz cm$^{-2}$ = 2.92%
WP efficiency > 95% @1.86 kHz cm$^{-2}$
Efficiency @2.03 kHz cm$^{-2}$ > 95%
Current densities

1.4-mm double-gap RPC @ $\text{Th} = 300 \, \mu\text{V}$

Avalanche charges

- vs gamma cluster rate
- vs gamma strip-hit rate
1.4-mm DRPC tested with gammas *(Avalanche charges)*

Mean charges, gamma cluster rates, and gamma strip-hit rates

At 300 uV (~ 50 fC): \( q_{el/strip} \approx 7.5 \text{ pC} \)
Dose distribution along the depth (44 MeV)

Dose distribution along the depth (190 MeV)

Vertex distribution of neutrons (44 MeV)

Vertex distribution of neutrons (190 MeV)
Responses to gamma

Time profiles

Channel distribution

Channel distribution x-y matched

x strips

y strips

x strips

y strips

x strips

y strips

x strips

y strips
2D response function for calibration (440 k γ) + random number generations for 20 times for smoothing

Image of three of ~ 3 μCi $^{60}$Co
Flood images
GEANT4 simulation for 44 MeV protons (FWHM = 3 cm) for KIRAMS test
Phantom size (biological tissue) = 3 cm x 16 cm x 16 cm

Dose distribution along the depth

Vertex distribution of $\gamma$

Dose distribution in the horizontal plane

Vertex distribution of $\gamma$ on the horizontal plane